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## LOAD-CARRYING CAPACITY TEST OF A LONG-SPAN TIMBER TRUSS

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### Abstract

The aim of this work was to study the behavior of existing timber trusses in order to improve the knowledge that may support engineers in the definition of more adequate restoration interventions in old buildings, particularly of long-span timber structures, as industrial or monumental constructions. For this purpose, a cyclic load-carrying test was carried out on a full-scale timber planar truss rescued from an old industrial roof structure. Before the tests, an accurate geometrical characterization was performed and the biological condition of the timber elements was evaluated by non-destructive tests to determine their effective cross-section. The results of the destructive load-carrying test were used to calibrate a numerical model which aimed to assess the effect of the effective cross-sections of the truss components and the axial stiffness of the joints on the overall response observed during loading. The full-scale test performed proved the importance of those kind of tests in order to assess the behavior of existing timber trusses. It is essential to assess the damage of the joints and to model correctly their behavior so as to numerically reproduce the overall behavior of timber trusses.

**Keywords:** Timber structures, Maintenance & inspection, Rehabilitation, reclamation & renovation

**List of notations:**

MC is the moisture content of wood

CoV is the coefficient of variation

LF are wire potentiometers

LV are the linear variable displacement transducers

$L$  is the longitudinal direction

$R$  is the radial direction

$T$  is the transversal direction

$E_0$  is the modulus of elasticity in the direction along the fibers

$E_{90}$  is the modulus of elasticity in the orthogonal direction of the fibers

$G$  is the shear modulus

$\nu$  is the Poisson's ratio

Nlink are nonlinear link elements

$k_{ax}$  is the axial stiffness of joints

$E_\alpha$  represents the wood elastic modulus in the direction forming an angle  $\alpha$  with the fiber

$l$  represents the nominal notch length, where compression deformation occurred

$S$  represents the nominal notch area

$k_{ax,hs}$  is the axial stiffness of the tie-beam/post connections

$E_{steel}$  is the modulus of elasticity of steel

$A_{heel}$  strap is the cross-section of the heel strap

$l_{heel}$  strap is the length of the heel strap

NDTs are non-destructive tests

## 1. Introduction

The assessment of existing timber structures requires, and relies, on the determination of the mechanical properties of the individual timber members, as well as on the behavior of joints and of structural system effects (Uzielli, 2004; Dietsch and Kreuzinger 2011; Fruhwald, 2011; Cruz et al., 2015). In existing timber structures, the first step in the safety assessment is the evaluation of the actual mechanical properties of the material (Riggio et al., 2013). Despite significant effort in the development of non-destructive testing, the strength of timber members can only be rigorously determined by destructive tests, which is often unacceptable in the case of historic buildings and other existing timber structures (Calderoni et al., 2010; Kasal, 2010).

In practice, it is the lack of knowledge about the mechanical properties of these materials and their structural behavior that normally leads to the replacement of existing wooden structures, instead of their retrofitting, to comply with the safety and serviceability requirements proposed in recent Codes and Recommendations. Moreover, the inaccurate characterization of the behavior of traditional timber roof structures can result in adverse stress distribution estimates in the members, as a result of inappropriate strengthening adopted in joints, in terms of stiffness and/or strength (Drdácký et al., 1999; Descamps et al., 2014). Thus, laboratory tests on scaled or full-scale specimens of members, connections and trusses are recognized as instruments that can provide valuable information for a better understanding of the behavior of traditional timber roof structures (Del Senno and Piazza, 2003; Bertolini-Cestari et al., 2013).

Portuguese traditional buildings are normally constituted by timber roof systems, with the truss being the main structural system for larger spans. Nowadays, a considerable number of timber roofs require structural intervention in consequence of natural degradation of the material, improper maintenance of the wood or of the structure itself, faulty design or construction, or accidental actions. A precise assessment of the extent of degradation and its effects in the overall structural system should precede any retrofitting action, which can vary from simple works in the covering system to substitution of structural members or joints/elements strengthening.

The assessed truss was saved from the roof structure of an old factory which was demolished in Avanca, Portugal. The truss was transported as a whole to the laboratory in spite of the difficulties involved. The decision to transport the truss in parts was ruled out because the state of degradation of the wooden members would have hindered the reassembling of the truss.

The roof was covered by ceramic tiles and its free span was 12.7 m while the slope was 26°. The main structure was composed of 13 similar Howe trusses made of Maritime pine (*Pinus pinaster*, Ait.) with an average spacing of 3.5 m. In Figure 1, the assessed Howe timber truss has been presented along with the average cross-section of each element and details of the main carpentry joints. The actual age of the truss structure isn't precisely known, but the factory has been known to exist since 1920 (Santos, 2009).

## 2. Visual inspection

A detailed visual inspection should be the starting point for any analysis of traditional timber structures. The visual inspection enables detection of external wood decay, as well as of visible mechanical damages. Moreover, it can be used to detect adverse climatic conditions in the past or present, as evidenced by moisture stains on exposed surfaces (Branco et al., 2010).

The visual inspection undertaken for the studied truss comprehended its geometric assessment and the state of conservation. A detailed inspection of each truss component was performed, while the dimensions of representative cross-sections of each element were measured.

During the visual inspection, it was evident that one side of the truss presented a more pronounced degradation. This is mainly a consequence of the cutting process of the timber elements that compose the truss. In fact, all the timber elements present an eccentricity of the pith in relation to the cross-section, resulting in different durability of the timber element faces. According to EN 350-2 and FICHA M2 (1997), this wood species is moderately to slightly resistant to fungi but susceptible to beetles, termites and marine borers, with the heartwood being extremely difficult to treat while the sapwood, easy to treat. However, for the service class corresponding to an industrial roof under cover and not exposed to the weather, practice shows that in the case of the Maritime pine (*Pinus pinaster*, Ait.), the heartwood can be assumed as durable to biological and insect attacks, in opposition to sapwood (FICHA M2, 1997). Figure 2 shows examples of cross-sections where the eccentricity of the pith is visible and the degradation is concentrated in the sapwood.

Visual inspection was also fundamental to perform a detailed geometric assessment of the various components of the truss, including the joints. In terms of joints, all are carpentry joints without tenons or pegs and most of them have a single step (notch). The ones that can be subjected to tension i.e. the joints of the posts with the tie-beam and rafters, additionally have steel plates (stirrups) of 5 mm thick and a width of 25 mm, nailed with square nails of 4 mm diameter spaced 50 mm apart (see Figure 1). During the preparation of the truss for testing and the transportation as a single piece to the laboratory, some joints developed gaps of significant size that were filled with wood in the case of compressed joints (Figures 3a and 3b). On the contrary, the separation between the king-post and the tie beam was restored by cutting the king-post by 20 mm along its length (Figure 3c). Moreover, one joint between the king-post and one rafter were partially rebuilt due to degradation in the king-post. The decayed part was replaced by a piece of the same wood species (Figures 3d-f).

In other hand, visual inspection allowed identifying the abnormalities of the material - wane, twist, bow and grain slope – and of the geometry of the truss – gaps in the joints, out-of-plane deformations of the elements and inappropriate contact between the king-post and the tie-beam. However, the main damage observed was the biological deterioration of timber caused by insects, which although mostly superficial (Figure 4), differed in the extent of damage (in depth) in the truss elements. From the visual inspection, a map of the damage distribution was produced, identifying and locating abnormalities and superficial deterioration (Figure 5). This map proved to be fundamental to plan and choose the type of non-destructive tests (NDTs) and where they would be carried out. These tests were done during the second phase, in order to evaluate the condition of

the timber components of the truss, beyond the superficial damage assessed through the visual inspection.

### **3. Non-destructive tests**

After the visual inspection, and based on the damage map produced, a series of non-destructive tests was planned aiming to characterize the extent of damage in order to assess the effective cross-section of each truss component. For this reason, two local non-destructive tests were applied: Pilodyn® and Resistograph®. While the visual inspection pointed out the superficial deterioration of timber, the Pilodyn®, a hardness test, measured the extent of degradation. In fact, the effects of degradation through the thickness of a timber element cannot be fully assessed by visual inspection or superficial tests. The Resistograph® test method allows measuring the timber resistance profile, drilling along the depth of the element, thereby detecting voids or defects inside the member. Since the results of both non-destructive tests are influenced by the presence of water, the moisture content of each component of the timber truss was measured, and the results obtained are presented in Table 1. Moisture content (MC) was measured using a hygrometer following the measuring scheme and procedure outlined in UNI 11035-1. The values measured were within the range 11.1%-14.3%, with a mean value of 12.5% and associated CoV of 6%.

#### **3.1. Pilodyn**

Pilodyn® is a non-destructive test that evaluates the superficial state of a wood structural member (superficial density, resistance and decay) through a penetration depth parameter. Pilodyn measurements can be used for the estimation of parameters such as density, mechanical properties and degradation. Unfortunately, in the case of decayed or damaged timber, the method encounters limitations associated with its superficial assessment essence.

The principle of operation is based on penetration (maximum of 40 mm) of a pin (diameter of 2.5 mm) in the wood element by means of a dynamic impact. The test output is the penetration depth.

Due to the superficial nature of the test, the use of Pilodyn® test results for the estimation of mechanical properties, should be used in combination with visual inspection (Branco et al., 2013). In this case study, Pilodyn® was used to assess the extent of the superficial deterioration of each timber element of the truss. By comparing the penetration depth measured in the non-deteriorated wood with the values in deteriorated zones, the extent of degradation is quantified and therefore, the effective cross-section can also be quantified. To systematize the results of the analysis, each timber element was divided into segments of 40 cm length. For each segment and for each side of the element, the mean value of the penetration depth was calculated as the average of 3 measurements. As an example, in Figure 6, the distribution of the penetration depth values

obtained in the North side has been plotted, with the more deteriorated portions corresponding to the sapwood.

### **3.2. Resistograph®**

The use of a small-diameter needle-like drill was introduced by (Rinn, 1992). The cutting resistance of a needle is recorded as a function of depth as the needle penetrates the timber. The resulting profile can be used to determine the location and extent of voids in the timber and/or variation in density. This technique is highly effective for quantifying the extent of deterioration in timber.

A total of 26 Resistograph® tests were performed on the truss under study, evaluating the depth of deterioration in representative points previously identified, based on the Pilodyn® penetration depth results, assessing the internal projection of anomalies visible from the exterior (Figure 7).

Two examples of graphs obtained with the Resistograph® are presented in Figure 8. Figure 8a presents the identification of the extent of the internal deterioration and Figure 8b shows the assessment of a ring shake, in two different sections. It is important to point out that the Resistograph® tests have only detected one section with an internal defect, namely, the one identified as R10.

## **4. Load-carrying test**

After the assessment of the timber truss condition, a quasi-static cyclic test was performed to evaluate its load-carrying capacity. The test setup reproduces the in-service load distribution applied on the truss, through five point loads representing the ridge and four purlins, simulating the points where the roof structure would settle. Those loads have been applied through five hydraulic actuators, fixed to the reaction floor of the Civil Engineering Laboratory of the University of Aveiro. Each actuator was linked to a chain embracing the rafter of the truss at each loading point (Figure 9). To guarantee the contact between all components of the truss, carpentry works were developed before testing, such as filling gaps and substituting decayed wood near the joints (Figure 10). To ensure the lateral stability of the truss during the in-plane loading test, a lateral bracing system consisting of steel tubes was built to avoid out-of-plane movements, as shown in Figure 11.

### **4.1. Load procedure**

The load-carrying test that was performed consisted of a symmetrical quasi-static cyclic (loading and unloading) test with cycles of increasing amplitude until the truss failure. The load cycles were performed with an increase in amplitude of 10 kN from cycle to cycle. In each cycle, after the peak load value was attained, the unloading was done until approximately 10 kN at each loading point, preventing the opening of the joint connections. A symmetrical load pattern was applied to simplify the loading procedure despite the fact that non-symmetrical loads can be more demanding.

However, the behaviour of the wooden truss structures can be characterized under symmetric loading conditions and in this test, the symmetric load distribution led to a non-symmetric response (Branco et al., 2010). Figure 12 presents the loading history (total load applied in each loading step) imposed by all hydraulic jacks during the test, up to a total of nine cycles, when failure occurred.

#### **4.2. Instrumentation**

Eighteen transducers were used to measure relative displacements during the load-carrying test, at the locations seen in Figure 13. Eleven wire potentiometers (LF) were used to measure the absolute displacement of points of the structure and seven LVDT's (LV) were used to measure the relative displacements between different elements of the truss. The relative rotation of the rafter-tie beam joints was calculated based on the values registered by two pairs of sensors, LV2-LV3 and LV10-LV11. Signals were recorded using a National Instruments DAQ device with 24 channels controlled by LabVIEW (Arêde et al., 2004).

#### **4.3. Truss response during the load-carrying test**

Timber structural elements normally have an elastic response when loaded. However, the response of truss structures under the cyclic loads may be highly non-linear (Branco et al., 2008; Branco et al., 2010). The unloading branch of each cycle normally presents residual, unrecoverable deformations (as represented in the example of Figure 14). During the first loading cycle, the most important adjustments of the truss elements take place, with closing of the gaps in the joints. Moreover, the type of connection (local embedment) of wooden elements, associated with the superficial degradation of the contact surfaces between elements, plays a key role in the non-linear response of the truss structures. This local non-linear behavior is observable in the unrecoverable rotation suffered by the rafter-tie beam joints after each loading-unloading cycle (Figure 15).

The combined effect of the local material degradation and the joint slip is observed in Figure 16. The slippage of the rafter relative to the tie-beam was monitored by an LVDT placed at the top of the rafter-tie beam joints.

The force-displacement response measured at the left joint (Figure 16) shows a slip due to the crushing of wood in the rafter and tie-beam. At the right joint (Figure 16), the slip measured is essentially due to the splitting of the tie-beam fibres (failure by shear parallel to the grain) in the final load cycle, while during most of the loading procedure the slip measured (by wood crushing) is less than that corresponding to the left joint. This shear damage observed is justified by the different degradation state of each of the connections. Moreover, on the right side of the tie-beam, the shake ring defect, i.e. internal fissures between the annual rings, significantly reduced the shear strength of that section. This faulty behavior of the right joint of the tie-beam-rafter explains the smaller relative rotation measured in this joint during the load-carrying test in comparison with the left joint (Figure 17).

The load was applied with an approximately symmetric distribution, with small differences, acceptable in tests of this complexity and scale. Despite the symmetric load distribution, the truss tie-beam presented a non-symmetric vertical deformation with a maximum value of 6.7 cm at LF8. Instrumented points LF7, LF15 and LF8 registered similar values for the displacement, while LF4 measured a vertical displacement which was 24% higher than the corresponding value in LF2. Figure 18 presents the vertical displacement of the truss tie-beam measured during the load-carrying test.

The connection between the tie-beam and the king-post, made by a metal plate embracing the tie-beam, worked properly during the entire cyclic loading test. This joint worked as a vertical support of the tie-beam, preventing vertical displacement, but allowing the connection to close, or in other words, it did not curtail the movement of the king-post towards the tie-beam (Figure 19). This analysis also clearly demonstrated the non-linear response of the truss with unrecoverable permanent deformations, associated with the behavior of the joints.

By subtracting the vertical displacements of the tie-beam from the values measured by the instruments located at both rafters, it is possible to assess the behavior of the joints between the other posts and the tie-beam. Figure 20 depicts the response of the joints between the tie-beam and the queen-post and princess-post, assuming that positive values correspond to a closing movement of the joint. Joints between the tie-beam and the queen-posts (LF7 and LF8) behave elastically in both directions, i.e. opening and closing as the load increases and decreases, respectively. The joint between the tie-beam and the left princess-post (LF2) presented a constant closing movement with very small opening movements during unloading. On the other hand, the right joint between the tie-beam and the princess post (LF4) showed a non-linear response with unrecoverable deformation towards closing.

The response of the joint between the king-post and the tie-beam can be assessed in two ways: subtracting the vertical displacement measured in LF15 from that in LF13 or analyzing the measurements registered by LV7 (see Figure 13). Despite the differences in both measurements, the behavior displayed is similar (Figure 21). This joint presents an elasto-plastic response, with an unrecoverable closing movement as the load applied increases with an elastic branch ( $\approx 0.1$  cm) which is recovered during unloading.

#### **4.4. Damage evolution and failure mechanism**

During the first loading cycle, no damage was observed. In the fifth load cycle, for a load of 60 kN, the local embedment of the wood in the left rafter-tie beam joint became visible due to the large displacements (Figure 22a). In the two subsequent loading cycles, with peak load values of 70 kN and 80 kN respectively, wood local embedment appeared on the right rafter-tie beam joint while, in the left joint, this damage was further developed (Figure 22b).

In the eighth loading cycle, for a load value of 85 kN, shear failure parallel to the grain was observed on the right rafter-tie beam (Figure 23a), based on the ring shake detected in the diagnosis phase (Figure 23b). Finally, in the ninth load cycle, for a load value of 95 kN, a complete shear failure

mechanism, parallel to the grain, occurred (Figure 23c). The slip magnitude in this joint led to a subsequent tension failure (disconnection) in the exterior joint of the strut-tie beam (Figure 24).

#### **4.5. Influence of the joints behavior in the overall response**

The behavior of the joints had a clear influence on the overall response of the truss. It was found that the natural defect (ring shake) present in the right rafter-tie beam joint led to the local failure mechanism and rupture of the truss. On the other hand, the joints played an important role in the deformation of the truss during the load-carrying test performed. The unrecoverable deformation observed after the first cycles (see Figure 14) results directly from the existence of gaps in the joints, despite the carpentry works of consolidation that were made (see Figure 3). But even after the gaps in the joints have been theoretically removed, the behavior of the joints conditioned the overall deformation of the truss. In particular, the slip (horizontal movement of the rafter) observed in the rafter-tie beam joints (see Figure 16) affects the overall deformation of the truss. With the slip in those joints, the entire superior part of the truss (above the tie-beam) moved down (proved by the closing movement observed in joint between the posts and the tie-beam, see Figure 20) pushing the tie-beam down and leading to an increase in the truss deformation. Moreover, this slip movement, which was more pronounced in the right rafter-tie beam joint, limited the capacity of those joints to rotate (see Figure 17).

### **5. Numerical modeling**

The structural analysis program SAP2000 (SAP2000, v9.0.3) has been used to model the tested structure. A model has been developed adopting beam elements with variable dimensions, and semi-rigid joints to simulate the connections between the different elements. A linear behavior is assumed for the material model.

#### **5.1. Material model**

Timber is taken to be an orthotropic material with anatomic cylindrical coordinates corresponding to the longitudinal,  $L$ , radial,  $R$ , and transversal,  $T$ , directions of the tree trunk. According to Mackerle (2005) and Parisi and Piazza (2000), the cylindrical coordinates may be approximated as orthogonal for the material extracted from the outer region of the trunk. In this case, the elastic moduli for an asymmetric model, are  $E_0$  in the direction along the fibers, and  $E_{90}$  orthogonal to it, plus a shear modulus,  $G$ , and a Poisson's ratio,  $\nu$ . In the absence of mechanical characterization tests, the values for the material properties were taken from FICHA M2 (1997) which defines the strength classes and the corresponding characteristic values for Portuguese Maritime pine.

#### **5.2. Geometric and mechanical models**

The geometry and loads on the truss permit the assumption of a plane stress model. The truss is analyzed as a frame structure, assuming elastic behavior for the members, while joints are modeled using nonlinear link elements (Nlink). The choice for the joints is justified by the ability of the link

element to simulate the semi-rigid behavior characteristics of traditional timber connections (Piazza et al., 2004; Parisi and Piazza, 2000). Moreover, those elements can be also used to simulate both extreme conditions, i.e. perfect hinges or rigid joints.

The timber members of the truss are modeled as beam elements with the cross-sections defined based on the dimensions obtained in the diagnosis phase, as reported in section 2. Therefore, in the model, each member was simulated by adopting 40 cm length elements with the cross-section dimensions obtained during the geometric assessment discounting the decay depth detected by Pilodyn and Resistograph® tests (see Figure 6).

### 5.3. Loads

For the analysis, two types of loads were applied on the truss. First, uniformly distributed loads that were automatically computed, were imposed on the elements to represent the self-weight of the truss members. Subsequently, cyclic vertical loads were applied at the joints, simulating the loading history adopted in the load-carrying test.

### 5.4. Semi-rigid modeling of connections

Traditional timber joints, even without any kind of strengthening, usually have a significant moment capacity (Parisi and Piazza, 2000; Branco et al., 2011; Candelpergher and Piazza, 2001). Common constraint models like hinges or full restraint connections, cannot satisfactorily describe the real behavior of these joints. However, in the case of the load-carrying test performed with symmetric loading, the rotational stiffness of connections has a trivial influence on the overall behavior of the tested truss (Branco et al, 2008; Branco et al., 2010). However, the axial stiffness of the connections is crucial in the truss response (deformation and stress distribution).

The axial stiffness ( $k_{ax}$ ) depends from the mechanical properties of the lumber, the geometric proportions of the connected elements and the connection angle (skew angle) (Piazza et al, 2004):

$$k_{ax} = \frac{E_{\alpha} \cdot S}{l} \quad (1)$$

where, applying the Hankinson Equation (2):

$$E_{\alpha} = \frac{E_0}{\cos^2 \alpha + \frac{E_0}{E_{90}} \sin^2 \alpha} \quad (2)$$

represents the wood elastic modulus in the direction forming an angle  $\alpha$  with the fiber,

$$l = \frac{h}{2 \cdot \sin \alpha} \quad (3)$$

represents the nominal notch length, where compression deformation occurred, and

$$S = \frac{A_{rafter}}{\sin \alpha} \quad (4)$$

represents the nominal notch area, where stress was assumed to be transmitted.

The axial stiffness of the tie-beam/post connections ( $k_{ax,hs}$ ) has been formulated taking into account the axial stiffness of the heel strap:

$$k_{ax,hs} = \frac{E_{steel} \cdot A_{heel\ strap}}{l_{heel\ strap}} \quad (5)$$

where  $E_{steel}$  is the modulus of elasticity of steel,  $A_{heel\ strap}$  and  $l_{heel\ strap}$  are the cross-section and the length of the heel strap, respectively.

A detailed explanation of the above expressions and the parameters involved can be found in previous works such as Piazza et al. (2004), Candelpergher and Piazza (2001), which are related to the numerical modelling of testing results of full-scale carpentry joints.

## 6. Numerical versus experimental results

The first simulations aimed to evaluate the reliability of the numerical model. The numerical analysis started with the investigation of the influence of the stiffness of the joints. Results of a model with joints simulated as hinges were compared with a similar model but with rigid joints. In both models, the cross-sections measured in the visual inspection, without taking into account the degradation depth (effective cross-section of the truss members), were assumed. Despite the differences between displacements levels, rigid joints led to smaller values of vertical displacements. Both models were unable to represent the asymmetric response of the truss observed (see Figure 18). The asymmetric response was reproduced only for the models where the cross-section of the beam elements had taken into account the wood deterioration. This outcome stresses, once again, the importance of the diagnosis phase, in particular, the adequate assessment of the effective cross sections of the timber members, for a reliable study of the behavior of timber trusses in old constructions.

After the validation of the options taken in terms of model for the joints (axial stiffness) and for the timber elements (beam elements with an effective cross-section measured each 40 cm length), the results of the numerical model were compared with the ones recorded during the load-carrying test. Comparing the results of the maximum vertical displacement of the truss measured during the load-carrying test and the ones obtained from the numerical model assuming the theoretical values for the joints axial stiffness, the latter values are only 28% of the former (see Table 2). From this, it was clear that the theoretical values for the axial stiffness of the joints were too large. The overall wood decay, especially at areas of higher stress concentration (joints), and the visible joint gaps, significantly reduced the initial axial stiffness of the joint. Despite the joint gaps identified in the visual inspection being filled with wood (Figure 3), the joint axial stiffness was not restored. So, a calibration process of the model was undertaken by reducing the axial stiffness values assumed for the joints. Numerically, adopting this simple model, only reducing the axial stiffness of the joints, it is possible to simulate the response of the joints during the load-carrying tests described in 4.5, and its consequence on the overall deformation of the truss.

Reducing the theoretical values of the axial stiffness of the joints by 20%, an average error of 28% was obtained when comparing the numerical results with the experimental ones. However, the observed non-symmetric deformation of the tie beam was not reproduced by the numerical model. Based on the observations during the load-carrying test, especially taking into account the failure

mode, it was decided to increase the reduction of the axial stiffness of the right rafter-tie beam joint (Nlink nº 22). When this local reduction reached 5% of the initial values, a good match was obtained between the numerical model results and the response obtained in the load-carrying test. Table 2 presents the comparison of the maximum vertical displacements of the truss measured during the load-carrying test and the corresponding values obtained with the numerical model for the most representative simulations.

In this calibration process, the material properties assumed for the wood were not taken into account due to the fact that no wood mechanical characterization was performed. Non-destructive tests were conducted to assess the effective cross-section of the truss components. In this case, however, their ability to predict the wood material properties is limited in the absence of destructive tests or since no reliable correlations between the test results and the material properties are known for this particular wood species. Moreover, the test performed demonstrated that the overall response of the timber truss is governed by the behavior of the joints, in particular, by their axial stiffness, and by the existence of defects detected by the visual inspection.

## **7. Conclusions**

The full-scale test conducted proved to be an important method to assess the overall performance of traditional timber trusses able to point out the localized behavior of joints. The experimental program yielded information and data difficult to assess using a different approach. The reasons that justify why those kind of tests are not so common are related with the scale of the experimental campaign, in terms of equipment and human resources that are need.

The test carried out demonstrated that after minor interventions aiming to recover the original joint mechanisms behaviour, the overall original behavior of timber trusses can be restored. The response is linear elastic with the non-linear behavior concentrated at the joints. In fact, the joints are the key elements in the overall behavior of the truss. The truss that was tested, presented localized damage at the joint between rafters and the tie-beam, which conditioned the failure mode of the system. Those joints are critical for the overall behavior of this kind of timber truss and, at same time, they are the ones more susceptible to degradation. Therefore, the assessment of the wood material pointing out local defects or damages, is crucial for an accurate interpretation and analysis of the global behavior of existing timber trusses. The truss failed due to a local damage detected previously, during the visual inspection of the truss.

A simple numerical model was implemented to reproduce the test carried out. This again proved that the diagnosis phase was crucial to define the effective cross-sections of the truss members. The non-symmetrical response observed during the load-carrying test was simulated only when the correct effective cross-sections of the truss elements, taking into account the degradation depth measured by the NDTs performed, was considered by the beam elements of the model. Then, as the loading procedure is symmetric, it is the joint axial stiffness that plays a crucial role in the response of the numerical model. The following simulations demonstrated that reducing the joint axial stiffness in order to take into account the existence of gaps and local degradation of joints,

significantly increases the accuracy of the numerical model. The trial and error process followed during modelling emphasizes the need for of defining a scientific procedure for the reduction of the joint axial stiffness.

Another source of discrepancy in the numerical results can be attributed to the material properties assumed for the wood. However, in practice, designers adopt the material properties values contained in literature without considering the possibility of carrying out a structural assessment based on reliability methods, as desired. Therefore, the authors chose to retain the material properties assumed in the numerical models.

As a final conclusion, it is suggested to develop a methodology to define how the gaps and initial damage and/or decay observed at the joints during the preliminary visual inspection can be taken into account in the joint axial stiffness reduction. There is detailed information available on the definition of the effective cross-section of timber elements and their material properties and the expression of the joint axial stiffness but, no information exists on how this stiffness is influenced by gaps and degradation. Full-scale tests, as the one presented here, represent the best methodology to assess how the damage observed on the joints reflects itself in the overall behavior of existing timber trusses. Therefore, such tests should be performed at every opportunity.

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## 8. References

- Arêde, A., Noites L., Costa, A., Sistemas de Monitorização de Ensaios de Estruturas de Engenharia Civil em Laboratório. NI Days 2004, LNEC, Lisboa, Portugal (in Portuguese).
- Bertolini-Cestari, C., Invernizzi, S., Marzi, T., Rolla, S. (2013), Preservation of the large timber roof of the Porta Nuova railway station in Torino. In: *Advanced materials research*, vol. 778, pp. 951-958.
- Branco, J.M., Cruz, P.J.S., Piazza, M., Varum, H., Field tests of a timber queen-post truss and numerical analysis, *SAHC 2008 - Structural Analysis of Historical Constructions*, Bath, UK, 02-04 July, 2008, 507-513.
- Branco, J.M., Piazza, M., Cruz, P.J.S., Structural analysis of two king-post timber trusses. Nondestructive evaluation and load-carrying tests. *Construction and Building Materials*. **24** (3), 371-383, 2010.
- Branco, J.M., Piazza, M., Cruz, P.J.S., Experimental evaluation of different strengthening techniques of traditional timber connections. *Engineering Structures*. 33 (8), 2011, 2259-2270.
- Calderoni, C., De Matteis, G., Giubileo, C., Mazzolani, F. M. (2010). Experimental correlations between destructive and non-destructive tests on ancient timber elements. *Engineering Structures*, 32 (2), 442-448.
- Candelpergher, L., Piazza, M., Mechanics of traditional connections with metal devices in timber roof structures. In *Proceedings of the Seventh International Conference STREMAH*, 2001, Bologna, Italy.
- Cruz, H., Yeomans, D., Tsakanika, E., Macchioni, N., Jorissen, A., Touza, M., Mannucci, M., & Lourenço, P. B. (2013). Guidelines for the on-site assessment of historic timber structures. *International Journal of Architectural Heritage*, 9 (3), 277-289, 2015.
- Dietsch, P, Kreuzinger, H, Guideline on the assessment of timber structures: Summary. *Engineering Structures*, 33 (11), 2983-2986, 2011.
- Del Senno, M., Piazza, M., Behaviour and rehabilitation of queen post timber trusses. A case study. In *STREMAH 2003: Structural Studies, Repairs and Maintenance of Heritage Architecture VIII*, May, Halkidiki, Greece.
- Descamps, T., Léoskool, L., Laplume, D., Van Parys, L., Aira, J.R., Sensitivity of timber hyperstatic frames to the stiffness of step and ridge joints. *World Conference on Timber Engineering*, Quebec, Canada, 2014.
- Drdácký, M., F. Wald, Z. Sokol, Sensitivity of historic timber structures to their joint response, in *Proc. 40th Anniversary Congress of the IASS*, Madrid, 1999.
- EN 350-2. Durability of wood and wood-based products — Natural durability of solid wood — Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe. European Committee for Standardization (CEN), Brussels, 1994.
- FICHA M2. Timber for structures – Maritime pine for structures. *LNEC National Laboratory of Civil Engineering* (eds), ISSN 0873-6472, Lisbon, 1997, 12 p. (in Portuguese).

- Frühwald, E, Analysis of structural failures in timber structures: Typical causes for failure and failure modes. *Engineering Structures*, 33 (11), 2978-2982, 2011.
- Kasal, B., State-of-the-art in in-situ assessment of timber, in RILEM TC AST 215 Special Publication. *Springer Verlag/RILEM Paris*, 2010.
- Mackerle, J., Finite element analyses in wood research: a bibliography. *Wood Science and Technology*, 39, 2005, 579-600.
- Parisi, M.A., Piazza, M., Mechanics of plain and retrofitted traditional timber connections. *Journal of Structural Engineering*, ASCE; 126(12), 2000, 1395–1403.
- Piazza, M., Brentari, G., Riggio, M.P. 2004. Strengthening and control methods for old timber trusses: the queen-post truss of the Trento theatre. In SAHC 2004: Structural Analysis of Historical Constructions, Padova, IT, II: 957–965.
- Riggio, M., Anthony, R.W., Augelli, F., Kasal, B., Lechner, T., Muller, W., Tannert, T. (2013), In situ assessment of structural timber using non-destructive techniques. *Materials and Structures*. May 2014, 47 (5), 749-766.
- Rinn, F, Chancen und grenzen bei der untersuchung von konstruk-tionsholzern mit der bohrwiderstandsmethode. *Bauen mit Holz*, 9:745–748, 1992.
- Santos, V.D.R., Evaluation of the behavior of large old timber trusses. Master thesis. Department of Civil Engineering, University of Aveiro, Portugal, 2009 (in Portuguese).
- SAP2000. Static and Dynamic Finite Element Analysis of Structures. Structural Analysis Program. Computers and Structures. Inc., Advanced 9.03. California. USA.
- UNI 11035-1. Structural timber – visual strength grading for Italian structural timbers: terminology and measurement of features. Ente Nazionale Italiano di Unificazione, 2003.
- Uzielli, L., Il manuale del Legno Strutturale, Vol IV - Interventi sulle strutture. *Mancosu*, Rome, Italy, in Italian, 2004.